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Predicting Residual Radiation from Beam Loss Monitor Data

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Abstract

Loss measurements from the Main Injector Beam Loss Monitor system have been recorded in the data logger since 11 October 2006. Residual radiation has been recorded using the ROTEM meter since 10 October 2005. By early 2010, thirty-eight data sets have been recorded where most data sets include measurements recorded at most of the monitoring points. We will develop a way to relate these measured results such that future residual radiation levels can be predicted based on Beam Loss measurements. Tools for managing and displaying the data and results will be described.

1 Introduction

The orbits used in Main Injector operation are quite stable. Most beam loss is at or near the injection energy of 8 GeV. Losses are dominated by the uncaptured beam loss and other effects of slip stack injection. Variations are frequently due to small changes in the Booster beam quality. As a result, we will assume that the geometry and energy of losses are always the same. With this assumption, the relation between Beam Loss Monitor (BLM) readings and residual radiation in the

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tunnel is fixed. We will explore our ability to correlate one BLM reading and residual radiation at some nearby point.

The basis for this statement lies in the following arguments:

1. For a fixed loss pattern (as assumed), the prompt radiation field produced by losses will produce a distribution of isotopes in the devices near the beam. The number of radioactive nuclei will be proportional to the beam lost.

2. This radiation field will also produce ionization in nearby Beam Loss Monitors (BLM's) and the ionization signal will also be proportional to the number of lost protons.

3. The radioactive nuclei will emit radiation including gamma rays which can be detected by the Geiger counter used to monitor residual radiation. At each monitor point, the efficiency with which the Geiger counter records signals due to the spatial pattern of isotopes and the spectra of the radioactive decays is dependent only on the isotope being detected.

We see that relation between the ionization signal and the residual radiation measured is linear such that all the energy dependent and geometric efficiencies can be combined into one coefficient per isotope, E_I. That isotope will have a half-life, τ_I.

There can be complications as the decay chain from the isotopes produced in the primary radiation field includes items of different activity levels and different lifetimes, but these secondary and tertiary isotope will still be proportional to the number of lost protons. They also have a fixed lifetime though the intermediate states may modify the decay curve to some extent. We will ignore this issue.

2 Asymptotic Formulas

To understand the expected performance, let us assume a constant loss rate L measured in the BLM. The residual, R, due to the production of one isotope, I by loss, L is

$$R = E_I \times L \tag{1}$$

correcting for isotope decay and integrating over time we find

$$R(T) = \int_{-\infty}^{T} E_I \times L(t) \times 2^{(T-t)/\tau_I} dt \tag{2}$$

The asymptotic residual radiation from this isotope can be found from from this integral assuming $L(t) = L$

$$R_A(T) = E_I \times L \int_{-\infty}^{T} 2^{(T-t)/\tau_I} dt \tag{3}$$

$$R_A(T) = E_I \times L \times \tau_I / \ln 2 \tag{4}$$

Since the number of radioactive nuclei of an isotope is related to the number of curies of that isotope by the half life or lifetime, we can think of this formula as expressing that $E_I/\ln 2$ relates the residual radiation detected per nuclei produced by L or $E_I \times \tau_I/\ln 2$ relates the residual radiation detected per curie of Isotope I.

We will fit our residual radiation measurements to the half-life-weighted BLM sums. Experience suggests that in most locations, the observed residual radiation has important components with half-life ranging from hours to months (with contributions from shorter half-life isotopes which have decayed before we enter the tunnel). This suggests that the values of E_I will have more comparable sizes if we fit to the loss rate, L, rather than the integrals.

3 Input Data and Analysis Formulas

Cycle integrated losses are measured and stored on each Main Injector cycle for each BLM channel. See Beams-doc-3299-v2[1] which describes loss monitoring and display tools for the Main Injector BLM system. Since we cannot enter the tunnel in less than half an hour, we are uninterested (for this purpose) in isotopes which have half lives of less than a few minutes. In practice, we consider isotopes with more than 2 hour half life. As a result, we sum the integrated loss from the BLM data record $LI(t)$, into 'quanta' over a summing interval T_s. Current practice employs T_s = 3600 sec = 10 minutes.

$$LI_j = \sum_{t=t_j}^{t_j+T_s} LI(t) \tag{5}$$

We will store data with this sum in the Sybase database for manipulation. For some purposes, we will wish to discuss the rate, $LR_j = LI_j/T_s$. We will store LI_j is units of Rads, although the results stored in the datalogger are in mRads. We will normally wish to examine LR_j in units of mRads/sec.

Residual radiation measurments have been taken with a ROTEM meter which stores results for a radiation survey of the ring in on-board memory. See Beams-doc-3523 v1[2], "Residual Radiation Monitoring in the Main Injector with the ROTEM RAM DA3-2000 Radiation Survey Meter" for details on these measurements. For a residual radiation measurement at time T_M, we weight the loss contribution for a specified isotope, I, with lifetime τ_I to produce the weighted loss sum. To make comparisons easier, we will express our integral as a loss rate by dividing by the half-life and normalizing with the factor ($\ln 2$).

$$LW(I,T_M) = \sum_j LI_j \times \frac{\ln 2}{\tau_I} 2^{-(T_M-T_j)/\tau_I} \tag{6}$$

The units for LW will be Rads/sec with half-life, τ_I and measurement times, T_M, T_j in seconds.[1]

The integrated loss at a location has produced some number of radioactive nuclei of various isotopes in some volume. For each isotope, we relate the detected radiation to the number of curies (decays) of that isotope. With our assumptions about constant geometry, all of the physics comes into one proportionality constant per isotope, E_I. This includes the geometry of the beam loss mechanism, the energy deposition shower shape with its resulting ionization in the loss monitors, the isotope production in the materials, the geometry relating the isotope spatial distribution to the probe position, and even the response of the Geiger tube to the radiation spectrum of the isotope.

As noted above, we will express our integrals as a loss rate to make comparisons easier.

$$RR(T_M) = \sum_I E_I \times LW(I,T_M) \tag{7}$$

This linear equation with one unknown per isotope per location relates the residual radiation measurement set to the weighted integral of the BLM readings. We typically will have more than

[1] A beam off time is recorded with each set of residual radiation measurements. It was inserted to allow very crude corrections for residual radiation decay. With BLM readings in use, it is mostly of value to locate data in which short halflife radiation may be significant.

20 measurements and expect to consider 3 or 4 isotopes at any location. The equation permits one to determine the set of E_I using the standard least squares method. Various errors will apply to the Residual Radiation readings but we will begin by only assuming a constant fractional error of 15% ascribed to the ROTEM meter by the manufacturer. As shown above, the units of RR are milliRoentgen/hr so with LW in Rad/sec, E_I will have units of Rad/sec per mR/hr. Fits to many locations give values of E_I between 0.1 and 1 $\times 10^{-4}$

3.1 Accounting for Old Residual Radiation

The residual radiation measurement system was in place before the current BLM electronics was implemented so we have some radiation history for which we have no BLM data. Since we have many places where the loss rate has dropped, sometimes to less than one tenth of its previous values, we will need to account for the existing residual radiation. However, the frequency of residual radiation measurements makes only the longest lived isotopes of interest. We can add this information to our fit by assuming only one long lived isotope. We know that ^{54}Mn with 312 day half life is important.

To add in old radiation measurement, let us take a measurement at time T_R, expecting but not requiring that it is before we have BLM data records. We assume that a fraction, f of that measurement is due to the long half life component with half life τ_L with the rest of the measured value coming from short lived components. For all subsequent measurements, the contribution from these previously created nuclei will be

$$\delta RR(T_M) = f \times RR(T_R) 2^{-(T_M - T_R)/\tau_L} \tag{8}$$

We simply add this contribution to the contributions ascribed to the losses recorded by the BLM record.

$$RR(T_M) = f \times RR(T_R) 2^{-(T_M - T_R)/\tau_L} + \sum_I E_I \times LW(I, T_M) \tag{9}$$

and we fit for the values of f and the several E_I.

Application program I130 is used to perform this fit. It uses a matrix inversion to fit for E_I with or without including the fraction f to account for older radiation. With limited measurements when the beam has been off a short time, and an unconstrained fit, fits for some pairs of RR, BLM result in negative coefficients, E_I. We will explore various half life values and various monitoring points and BLM's to establish general patterns. Alternative fitting solutions can be developed to apply this parameterization.

4 Loss Averages

In order to plan for radiation exposure when working in the tunnel, we have usually relied on the fact that loss rates are like the past or even decreasing. We will now hope to examine the BLM data record to refine our expectations. Using fitted coefficients, E_I, and suitable weighted loss rates, one can calculate detailed predictions of the time decay of radiation. To assist in understanding these results and relating them to operational considerations, we also calcualate running averages so that the impact of simple average rates can be understood, roughly. Let us define an average loss at time T_M for interval T_A as

$$LA(T_A, T_M) = \sum_j \frac{LI_j}{T_A} \tag{10}$$

where the sum is taken over the interval T_A which ends at T_M. We refer to these as running average loss rates. As above, we will express these rates in mRads/sec. The rates LW defined above are traditionally called exponentially weighted moving averages.

We will provide weekly values and plots for LW for ${}^{54}Mn$ with 312 day half life and ${}^{52}Mn$ with 5.59 day half life and LA for averaging intervals of 7 days (1 week) and 315 days (45 weeks). These graphs will make the impact of loss changes apparent and the current values of LW can be used to make detailed predictions. The definitions have been chosen so that LW and LA will approach each other for extended periods of constant loss.

References

[1] Bruce C. Brown and Guan H. Wu. Some Console Applications for Displaying Main Injector BLM Measurements. Beams-doc 3299 v2, Fermilab, June 2009.

[2] Bruce C. Brown. Residual Radiation Monitoring in the Main Injector with the ROTEM RAM DA3-2000 Radiation Survey Meter. Beams-doc 3523 v1, Fermilab, December 2009.